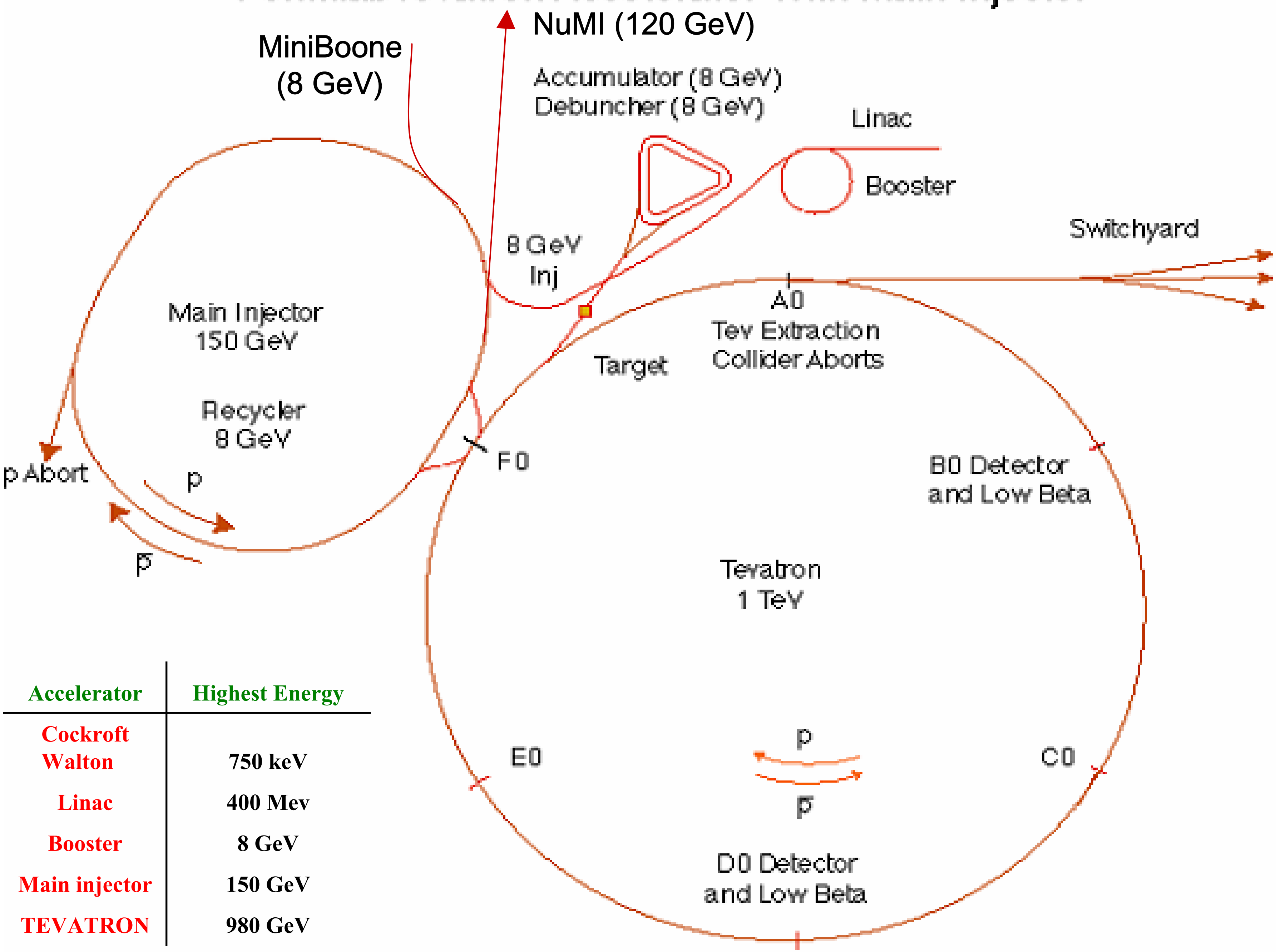
FNAL Accelerator Complex 101: What's Happening in the Machines?

Ron Moore – FNAL

- Accelerator Complex Overview
- Shot-Setup
- Miscellany

FermilabTevatron Accelerator With Main Injector



Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

Proton Source

- 25 keV H^- ion source
- 750 keV Cockcroft-Walton accelerator

- Linac: accelerate H^- ions to 400 MeV
  - 116 MeV Alvarez linac (201.25MHz)
  - 400 MeV side-coupled cavity linac (805 MHz)

- Booster: 8 GeV synchrotron
  - Runs at 15 Hz
  - Stripper foil at injection removes electrons from H^- ions
  - Accelerates protons from 400 MeV to 8 GeV
  - Most protons (>75%) going through Booster are delivered to MiniBoone (eventually NuMI)

Main Injector (MI)

- Replaced Main Ring (formerly in Tev tunnel)
  - Higher repetition rate for stacking pbars
  - Simultaneous stacking and fixed target running
- Many operating modes
  - Pbar production: ~ $6\text{-}7 \times 10^{12}$ 120 GeV protons to pbar target
    - "Slip-stacking" – merge two booster batches of beam on 1 MI ramp cycle
  - Tevatron protons/pbars:
    - Accelerate 8 GeV to 150 GeV
    - Coalesce 7-9 proton bunches 90% eff into 270-300 E9 bunch
    - Coalesce 5-7 pbar bunches 75-90% eff into 20-80 E9 bunch
  - Transfer 8 GeV protons/pbars to the Recycler
  - Provide protons for neutrino production
    - 8 GeV protons for MiniBoone
    - 120 GeV protons for NuMI
  - 120 GeV protons to Switchyard (fixed target area)

Pbar Source

- > $6*10^{12}$ protons per pulse (120 GeV) strike Ni target every 2-3 sec
- Li lens (740 Tesla/m) collects negative secondaries
- Pulsed dipole "PMAG" bends pbars down AP-2 line to Debuncher
- Pbars "debunched", cooled briefly in Debuncher prior to Accumulator
- Stack rate = 6-14 mA/hr depending on stack size
  - Limited by stochastic cooling systems in Accumulator
  - Hope to exceed 18 mA/hr this fiscal year
- Efficiency ≈ $(13\text{-}18)*10^{-6}$ pbars/proton on target
- Transverse beam size increases linearly with stack size
  - That's a drawback…

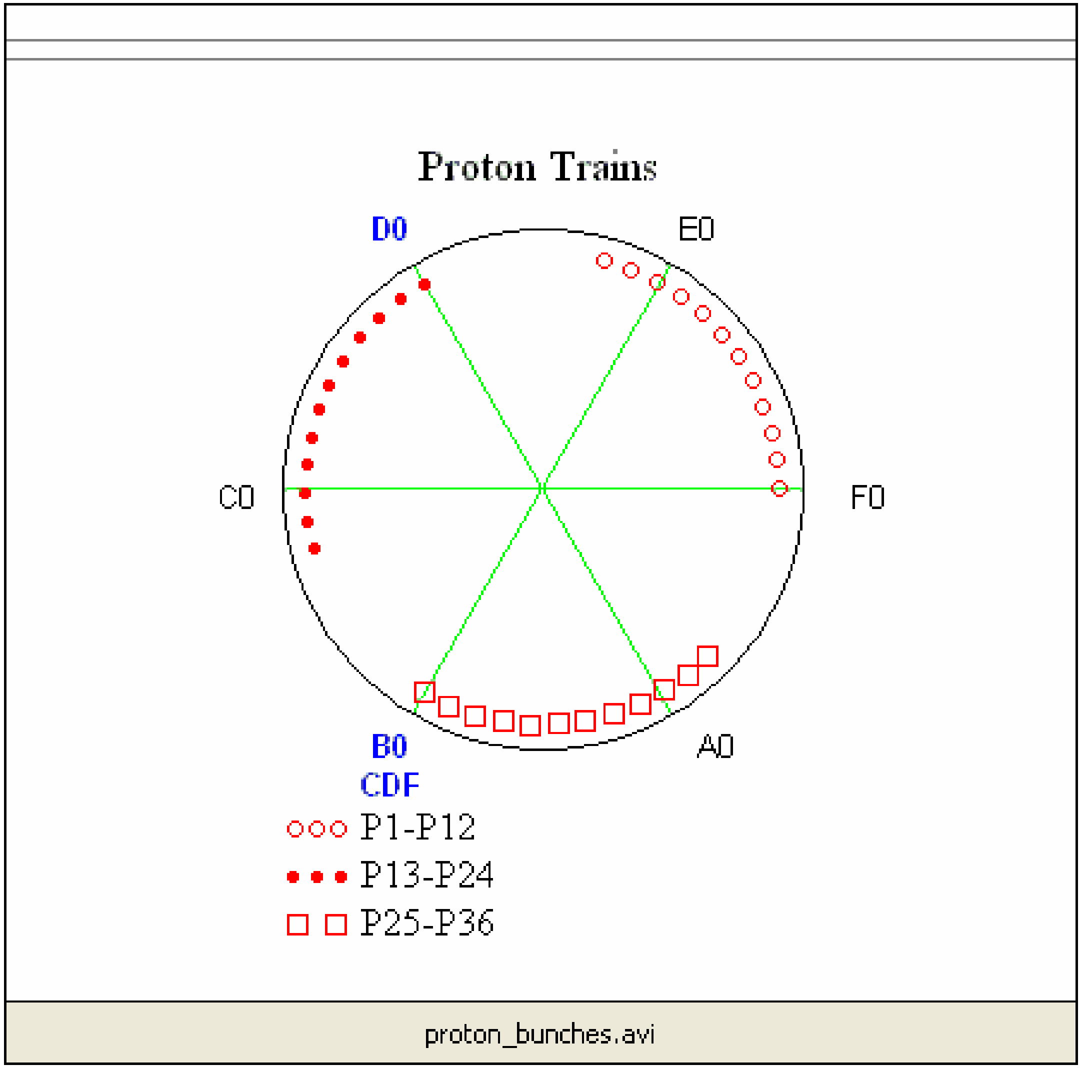
Recycler (RR)

- Fixed energy (8 GeV), permanent magnet storage ring in MI tunnel
  - There are some powered correctors
- Originally supposed to “recycle” pbars left over from a Tevatron store
- Now will be used as intermediate pbar storage ring
  - Build small stack in Accumulator, transfer to Recycler; repeat…
  - Take advantage of high Accumulator stacking rates for small stacks
- Electron cooling needed for large stashes
- Eventually, all pbars for Tevatron will come from Recycler

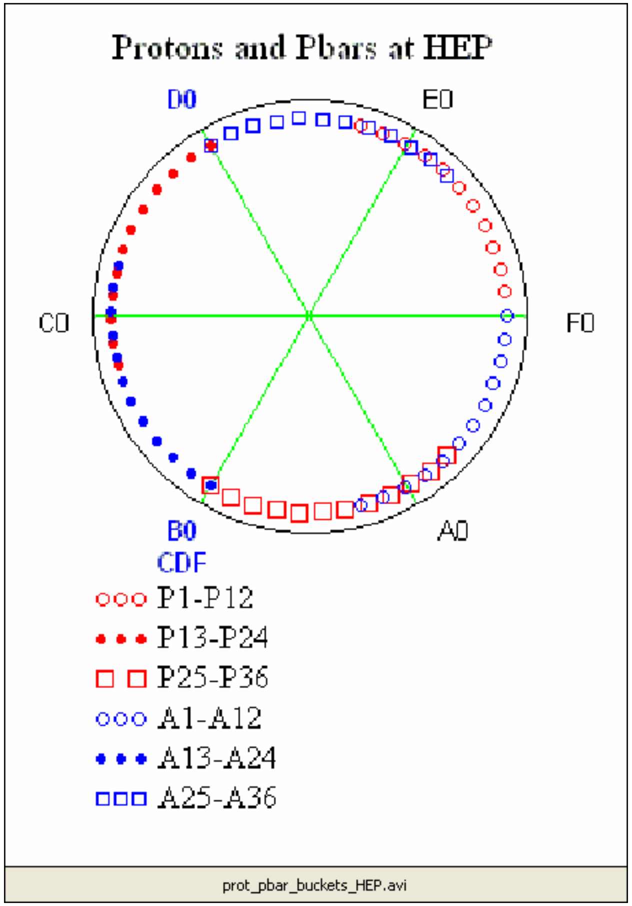
Tevatron Overview

- Provides proton-pbar collisions @ 980 GeV beam energy
- Tevatron radius = 1 km $\Rightarrow$ revolution time ~ 21 μs
- Virtually all of the Tevatron magnets are superconducting
  - Cooled by liquid helium, operate at 4 K
- 36 bunches of proton and pbars circulate in same beampipe
  - Electrostatic separators keep beams apart
- Injection energy is 150 GeV
  - Protons injected from P1 line at F17
  - Pbars injected from A1 line at E48
- 3 trains of 12 bunches with 396 ns separation
- 2 low β (small beam size) intersection points (CDF and D0)
- 8 RF cavities (near F0) to keep beam in bucket, acceleration
  - 1113 RF buckets (53.1 MHz $\Rightarrow$ 18.8 ns bucket length)

Proton Bunch Positions

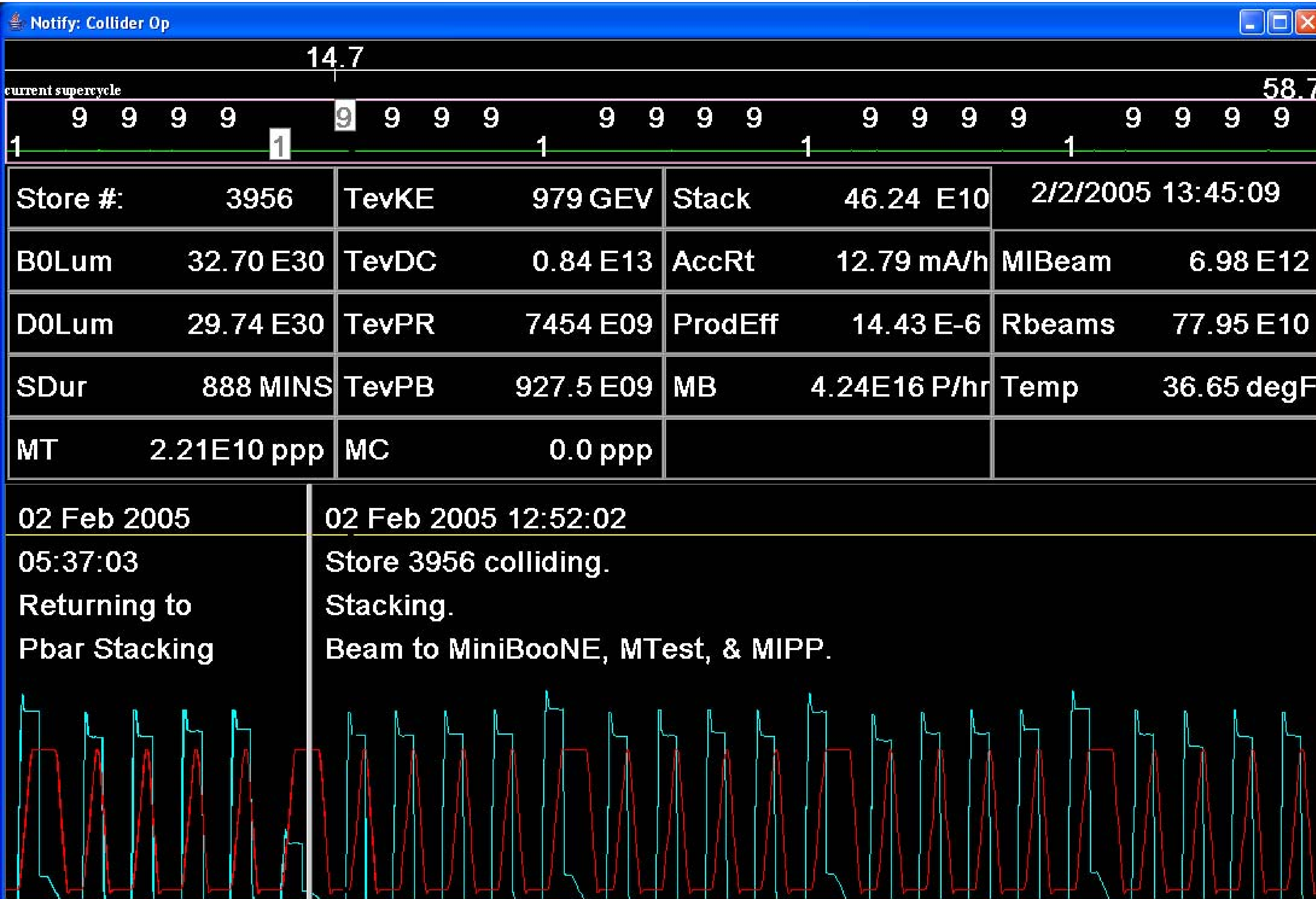


Protons and Pbars at HEP



Proton bunches	Collide @ CDF	Collide @ D0
P1-P12	A25-A36	A13-A24
P13-P24	A1-A12	A25-A36
P25-P36	A13-A24	A1-A12

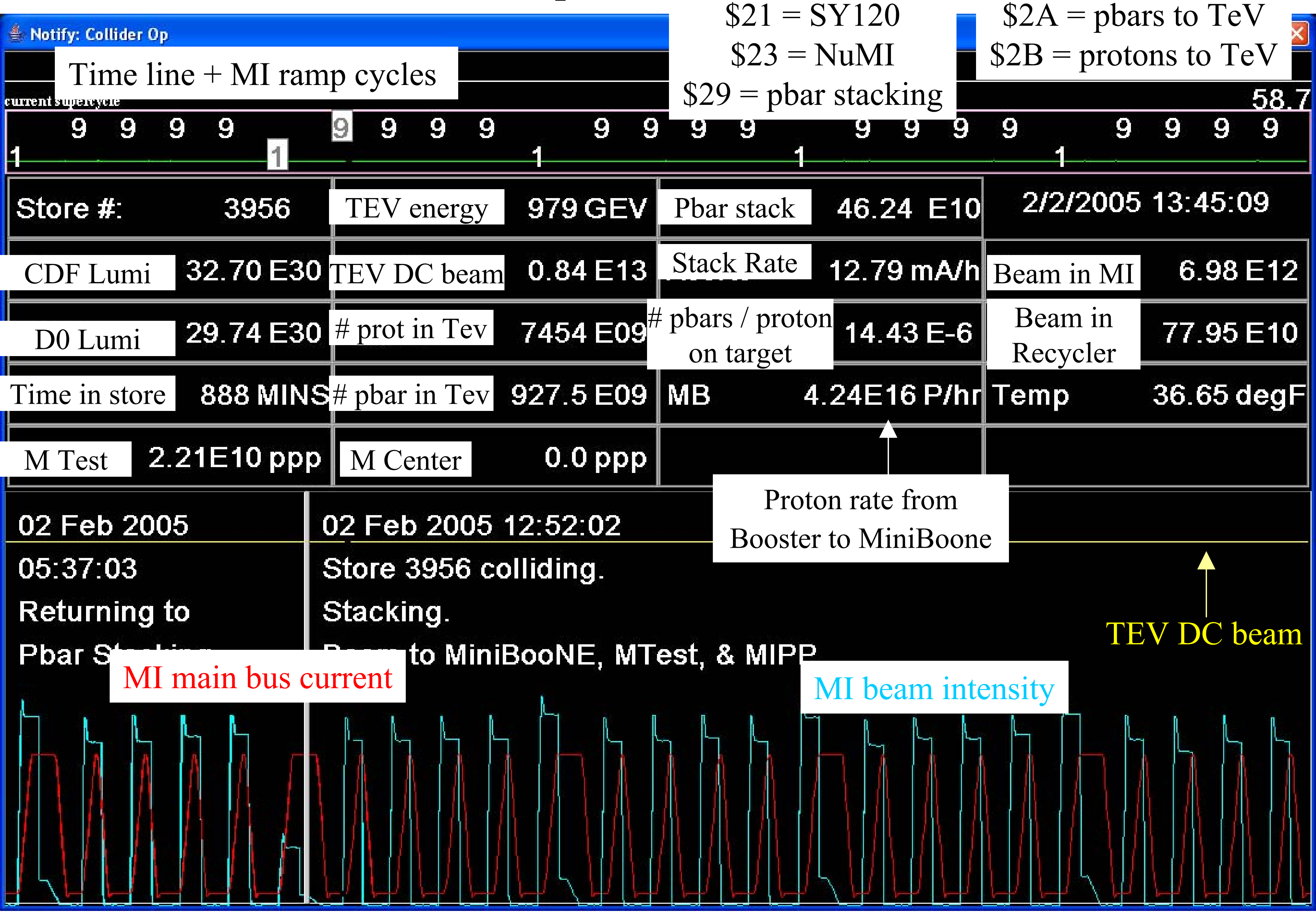
Channel 13, a.k.a "Notify"



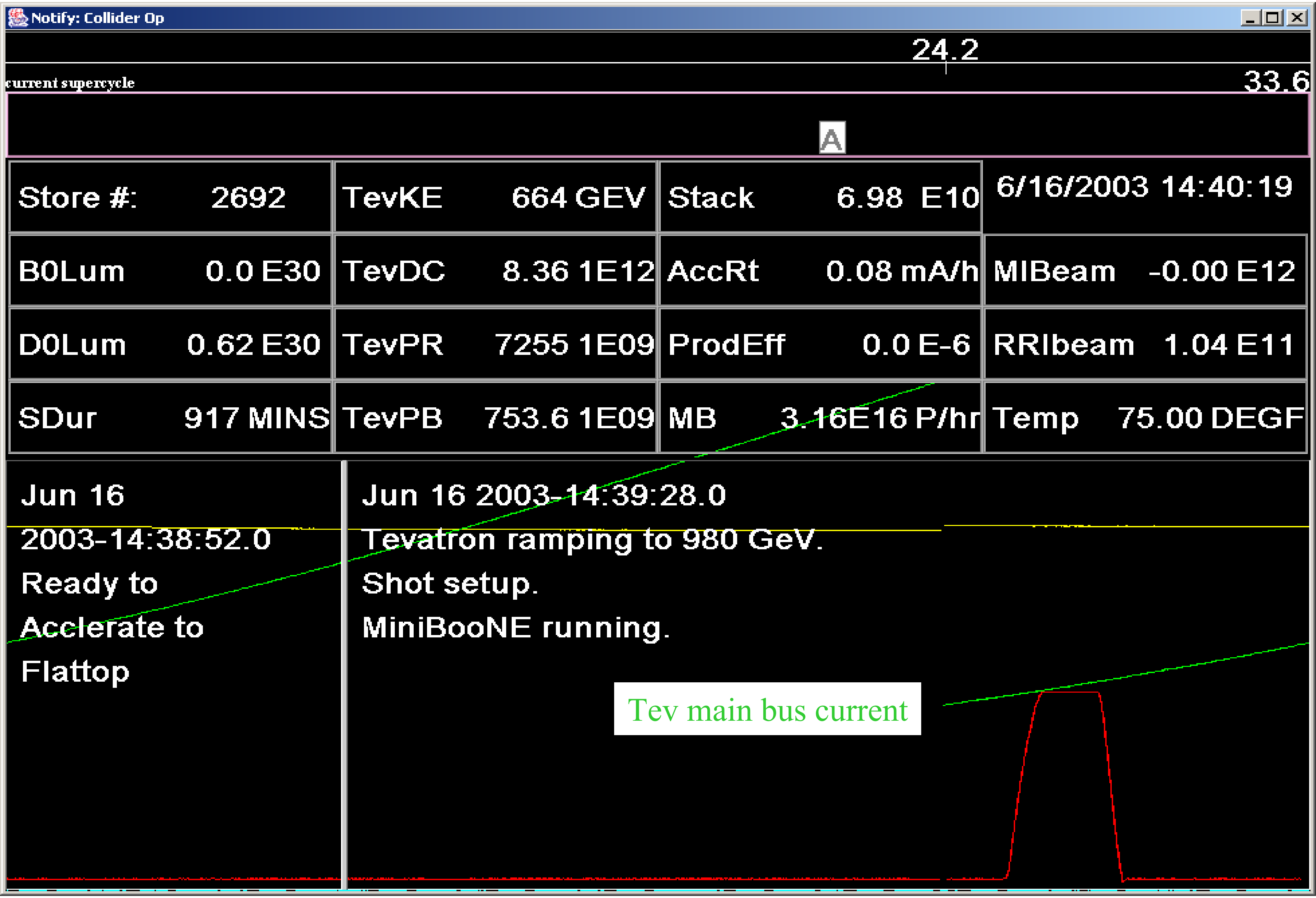
Channel 13 with help

120 GeV cycles
$21 = SY120
$23 = NuMI
$29 = pbar stacking

150 GeV cycles
$2A = pbars to TeV
$2B = protons to TeV



Channel 13 (old) while Tev is ramping



Prior to Shot-Setup

- Run Coordinator decides when to end store
- Experiments turn off HV after MCR calls
- Experiments call MCR to confirm they are ready
- Tev abort kickers fire driving beam into A0 dump blocks

- Tev unsqueezes, ramps down to 150 GeV
- Tev ramps, squeezes, sits at low β for 20 min, return to 150 GeV
  - **Eliminated this step by better compensation of eddy current effects**
  - "Dry squeeze" $\Rightarrow$ no beam (good time for calibrations)
  - Resets magnet fields to "known" condition
  - Sometimes "wet squeeze" (uncoalesced beam) to gather orbit data

- At 150 GeV, Tev begins shot-setup with beam

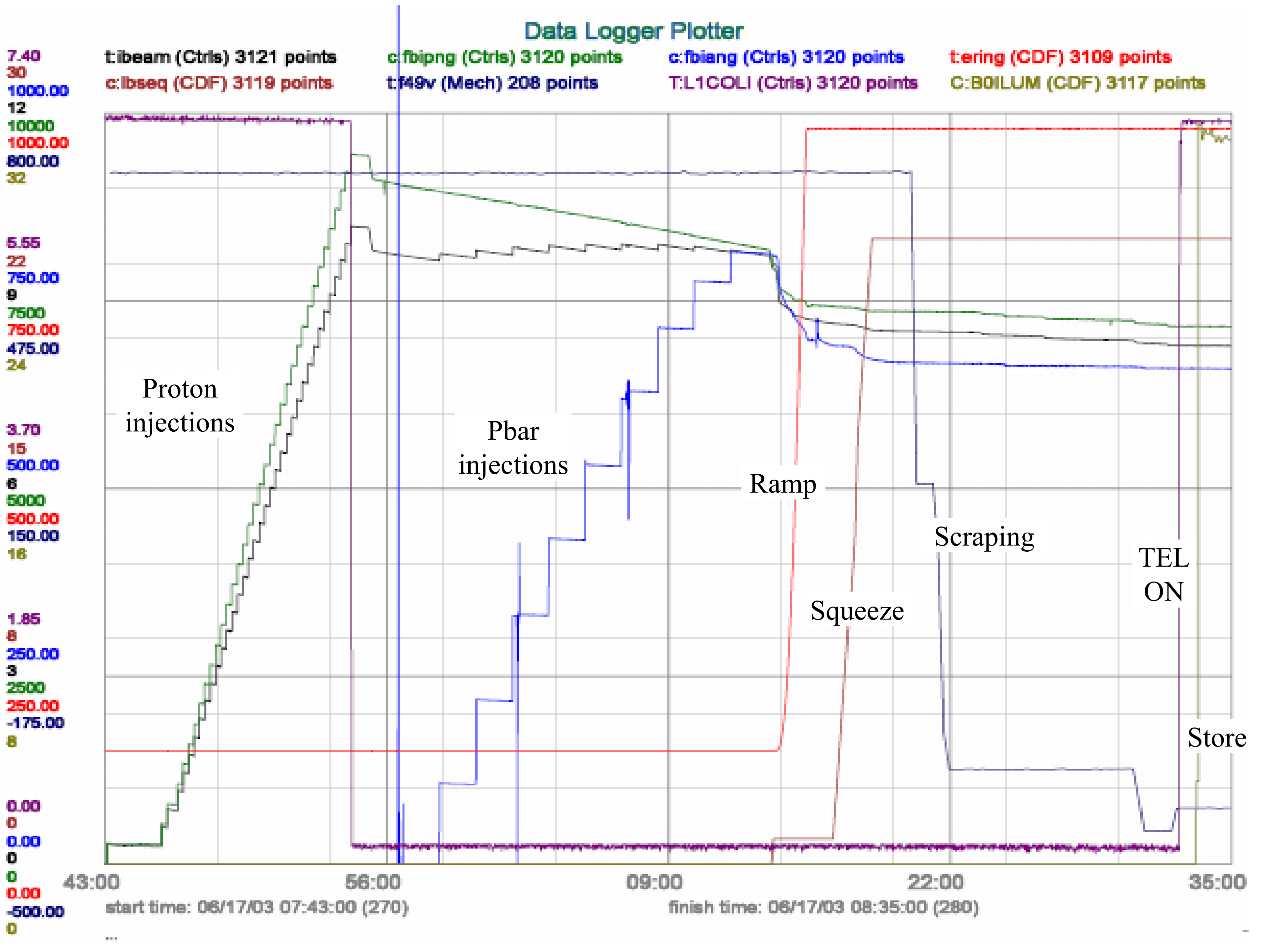
- Meanwhile, pbar starts "cooling" the stack, then changes Accumulator to "shot lattice" in preparation for shot-setup

Shot Setup Overview

- MCR crew performs beam line tune-up for Pbar, Main Injector, and Tevatron
  - Make sure extracted beams are injected into next machine on, or very close to, desired orbit
  - Helps reduce oscillations that cause emittance (size) growth
- MCR crew also sets Tevatron tune, chromaticity, coupling to desired values @ 150 GeV
  - Important for beam lifetimes
- Shots can begin once all the machine and beam-line tune-ups are complete.

Shots to the Tevatron

- Protons are injected first (onto central orbit) 1 bunch at a time
- Separators turned on to put protons on helical orbit
- Pbars are injected 4 bunches at a time into abort gaps
  - After 3^{rd} and 6^{th} pbar transfers, pbars cogged to empty the gaps
- Accelerate beams to 980 GeV (~90 sec)
- Final pbar cogging to collision position
- Low Beta Squeeze (~ 2 minutes)
- Initiate Collisions (change separator voltage around IPs)
- Scraping (~12-15 minutes)
- Turn on TEL (knocks out beam from the abort gap)
- MCR declares store ready for HEP
- Typical time from store end to start of new store: 2-3 hours
- Once losses are low and beam is stable, ramp the HV and begin taking data



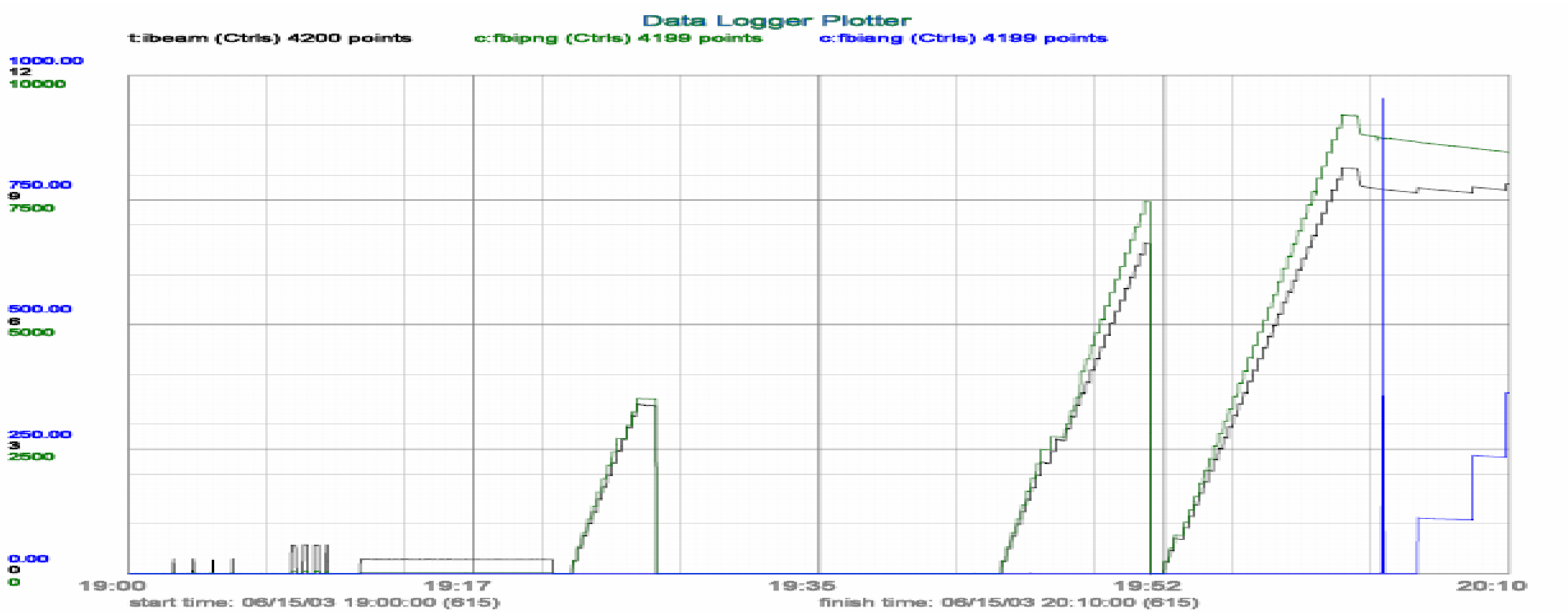
Data Logger Plotter
t:ibeam (Ctrls) 3121 points
c:fbipng (Ctrls) 3120 points
c:fbiang (Ctrls) 3120 points
t:ering (CDF) 3109 points
c:lbseq (CDF) 3119 points
t:f49v (Mech) 208 points
T:L1COLI (Ctrls) 3120 points
C:B0ILUM (CDF) 3117 points
Proton injections
Pbar injections
Ramp
Squeeze
Scraping
TEL ON
Store
43:00
56:00
09:00
22:00
35:00
start time: 06/17/03 07:43:00 (270)
finish time: 06/17/03 08:35:00 (280)

While the Tevatron Has a Store…

- Pbar stacking begins after Tev scraping complete
  - 120 GeV proton pulses in P2 line could affect loss monitors used for feedback during scraping (P2 line in Tev tunnel)
- Protons delivered to MiniBoone, Switchyard, and NuMI
- Main Injector & Recycler studies can occur (as long their cycles don't occupy too much time in the time line)
- Shoot pbars from Accumulator to Recycler
- MCR crew monitors store, responds to CDF/D0 requests, e.g., reduce losses
  - A Tev expert always on-call to assist
- MCR crew also busy monitoring stacking, MiniBoone, helping studiers, fixing problems…they are vital to us all!

Injecting "Final" Protons

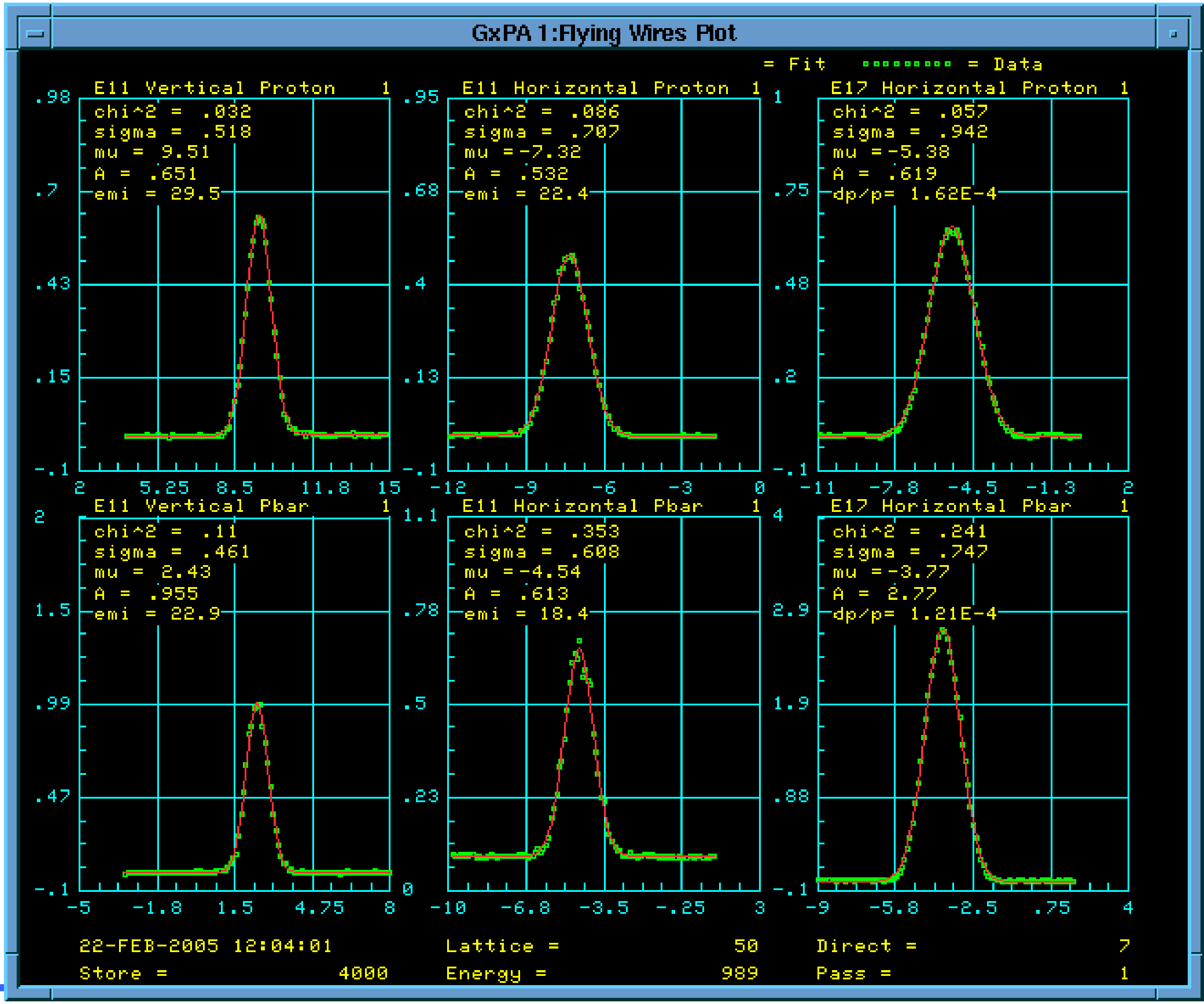
- Protons can be injected into Tev every 15 sec. (Limited by MI average magnet power.)
- Each proton bunch is "qualified" in the Main Injector.
  - If bunch below minimum intensity, it goes to MI dump, not the Tevatron
  - Purpose is consistency among the proton bunches
- While loading "final" protons, MCR often tunes on intensities, emittances
- If loaded protons don't have desired qualities, MCR may abort <u>intentionally</u>.
  - We seldom "lose" the injected protons during shot-setup.
  - Occasionally it may take 2 or 3 attempts to load protons as desired.



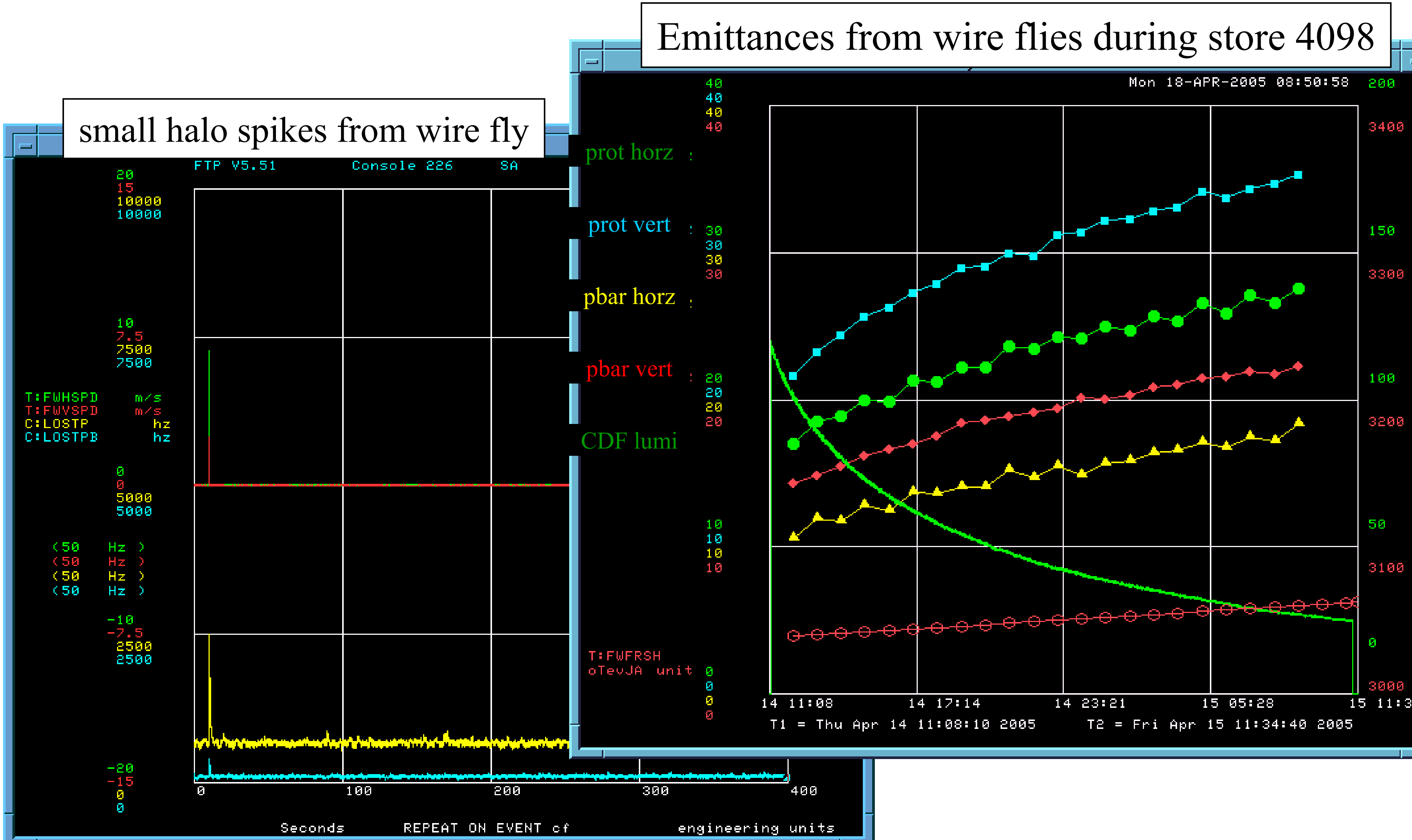
Flying Wires

- Fly wires through beams
- Scatted particles detected in scintillator paddles
- Can cause loss spikes in CDF/D0
- Measure transverse beam profiles

- New wires @ E11 are thinner (7 μm), cause less loss
- Want to fly every hour or so to see emittance evolution



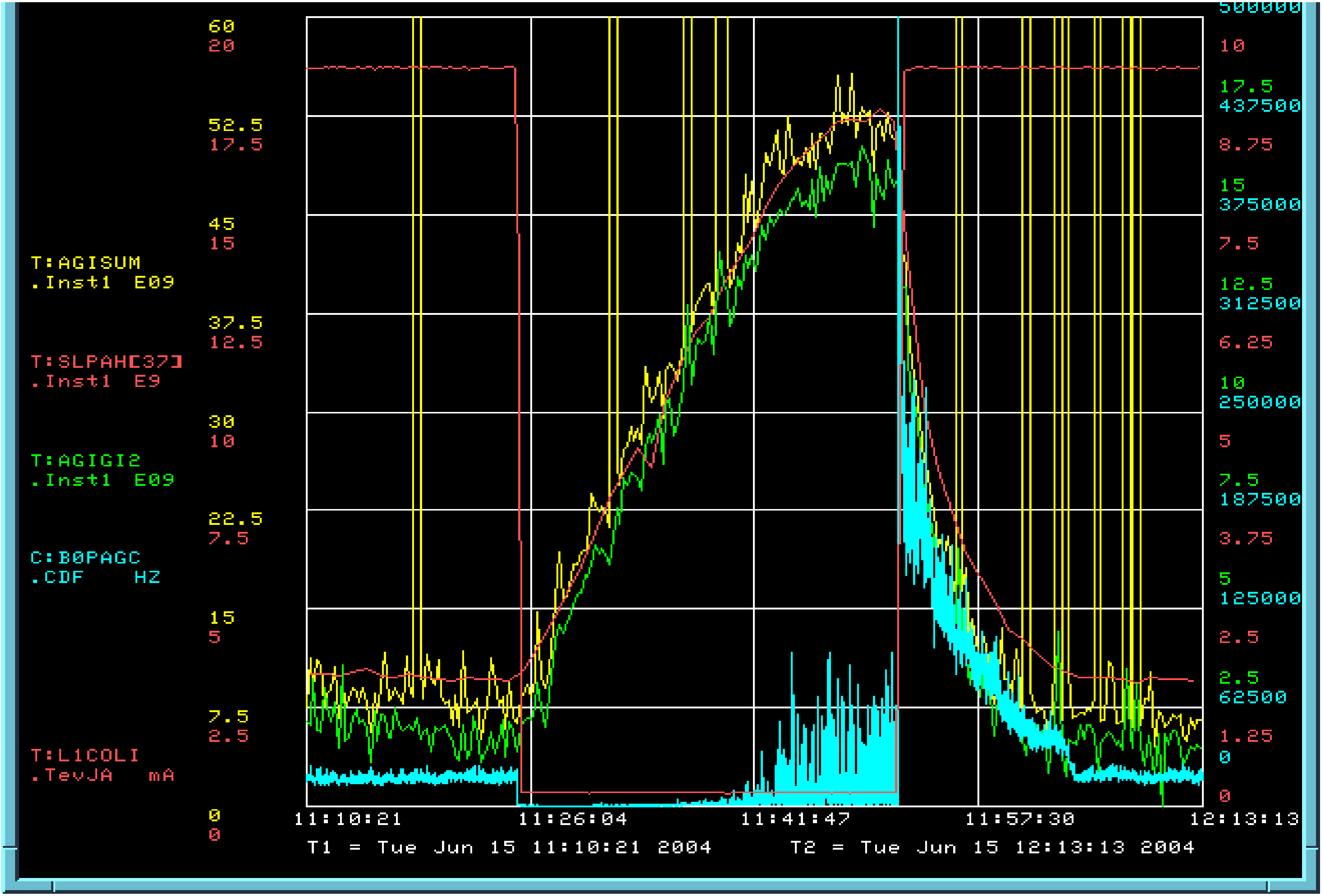
Flying Wires (2)



Abort Gap Monitors

- Until last summer, scintillator paddles near CDF (C:B0PAGC) were the only means of estimating amount of DC beam in the abort gaps.
  - Not ideal – really only sees beam being lost from the gap (TEL or otherwise) that is not absorbed by a collimator
  - Can vary even if real beam intensity in abort gap does not
- Now use synch light system to image <u>directly</u> beam in the gaps.
  - T:AGIGI1, T:AGIGI2, T:AGIG3, T:AGISUM = use a gated PMT to look at a beam of synch light split inside the synch light box
  - T:SLPAH[37] = uses the MCP (micro-channel plate) of the original synch light system (better for LOTS of beam in abort gap)
- We (MCR, Tev) use T:AGIGI2 to determine safe levels of DC beam and how to reduce it if needed
  - >45 E9 (?) beam in gap can cause a quench when abort kickers fire (on helix, with collimators in)

Testing Abort Gap Monitors

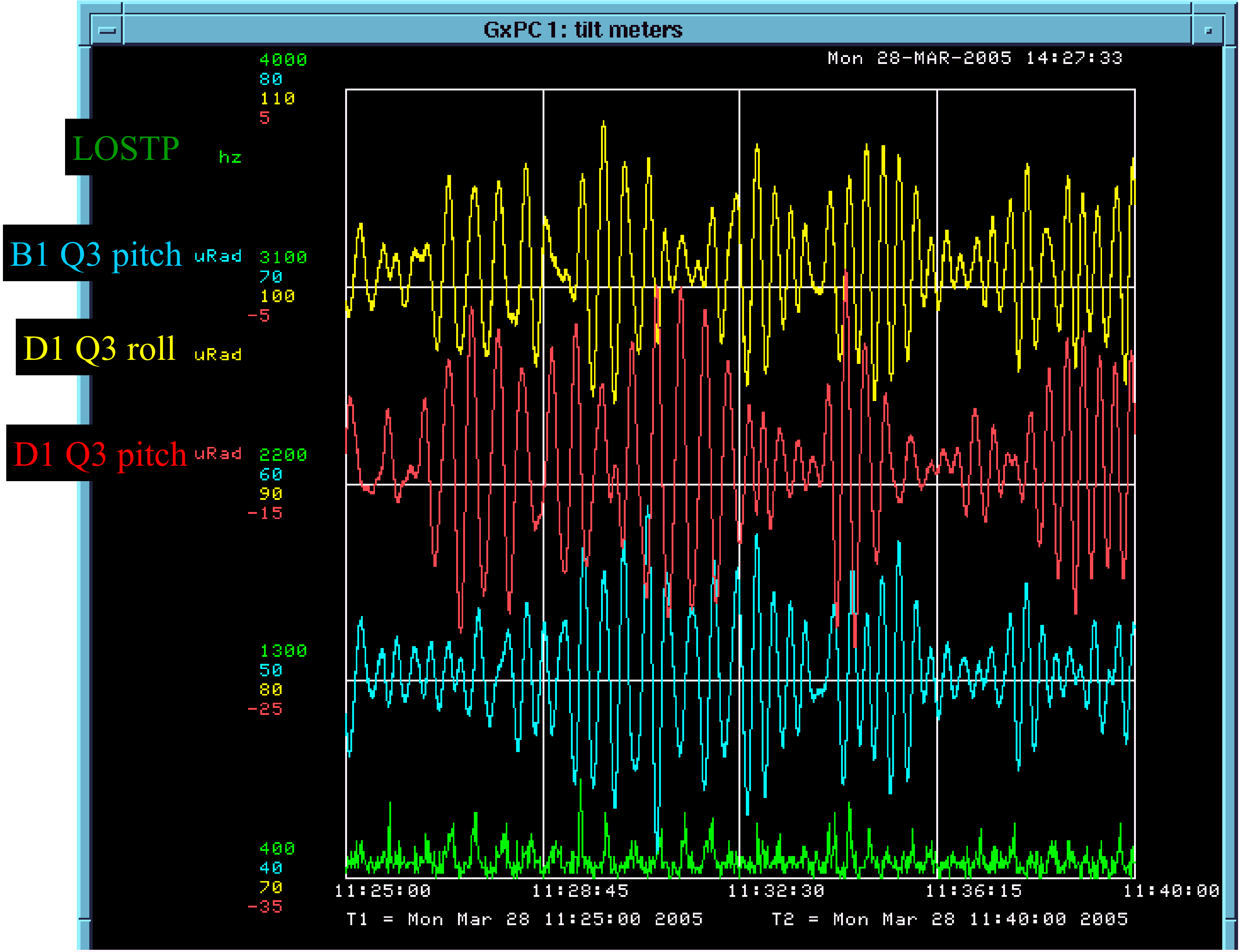


Halo spikes from vibrating/moving quads

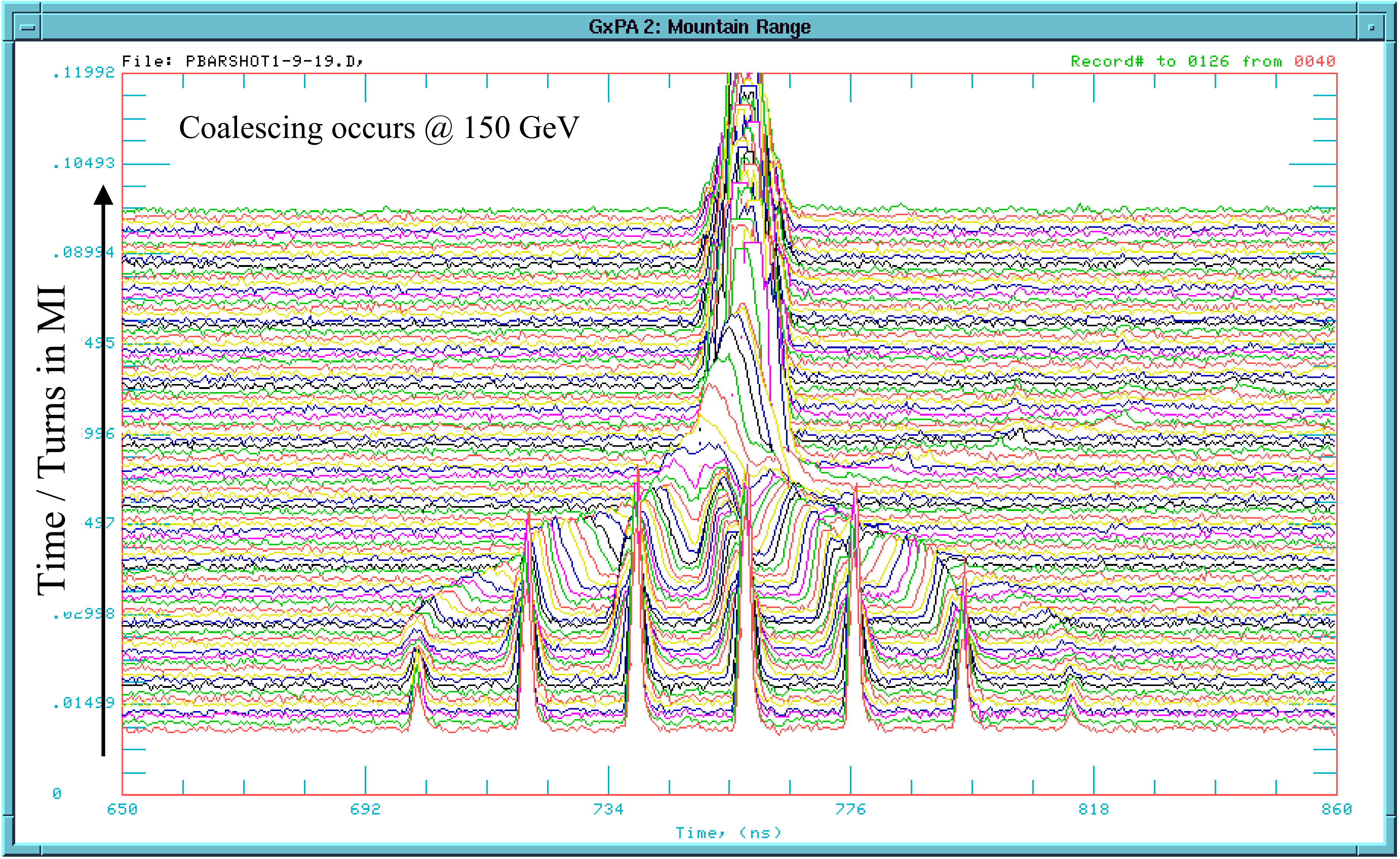
- Quad motion imparts a kick to the beam that can drive it toward a collimator and cause a spike in losses
- Low beta quad girder now supported from below
  - Before last shutdown, quads hung from the collision hall ceiling
  - Quads now seem more stable, loss spikes less frequent
  - Temperature changes can still cause elevated losses
- C:BQUAKE = ground motion detector in the B0 service building
- C:AQ3VPK = tiltmeter/peak detector on A4Q3 quad in the CDF hall
- T:ORBITH/T:ORBITV = horz/vert “latched” orbit peak detectors

- We haven’t had a real earthquake for a while…

Sumatra Earthquake 3/28/05



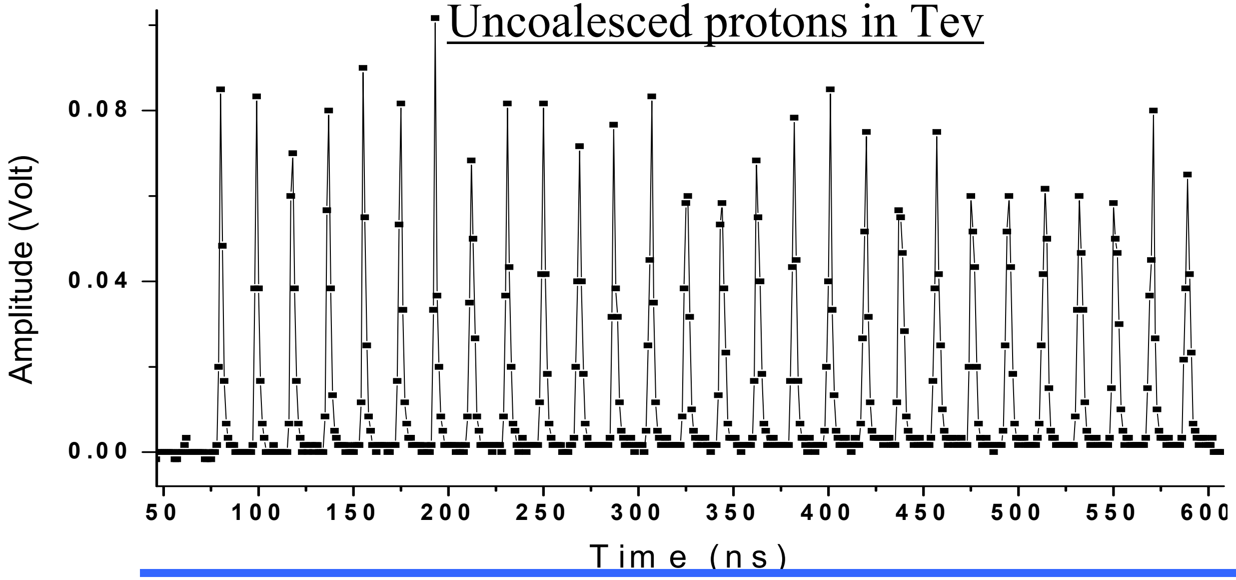
Pbar Coalescing in Main Injector



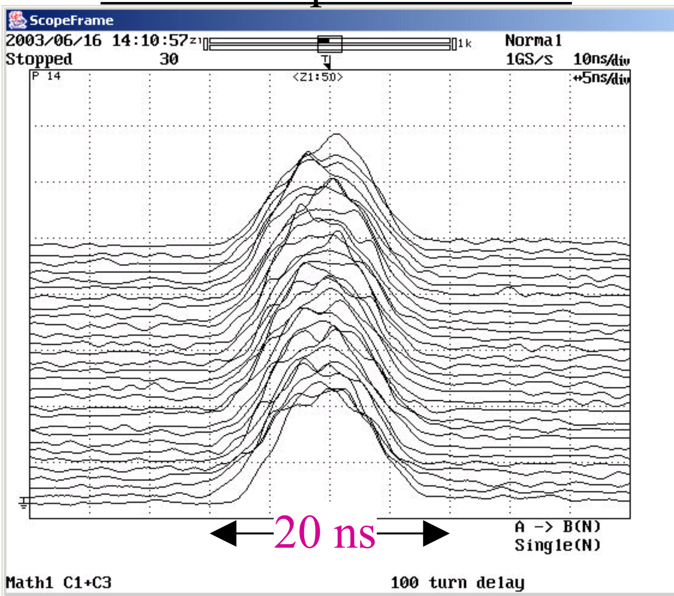
Coalesced vs Uncoalesced Beam in Tev

- Uncoalesced
  - 30 or so consecutive RF buckets filled with ~10 E9 protons/bunch
  - Usually used for machine tune-up, studies
  - Protons only   (well, pbars can be uncoalesced if needed for some study)
- Coalesced
  - 5-7 buckets of beam merged into a single RF bucket at 150 GeV in MI
  - Protons and pbars always coalesced for HEP stores

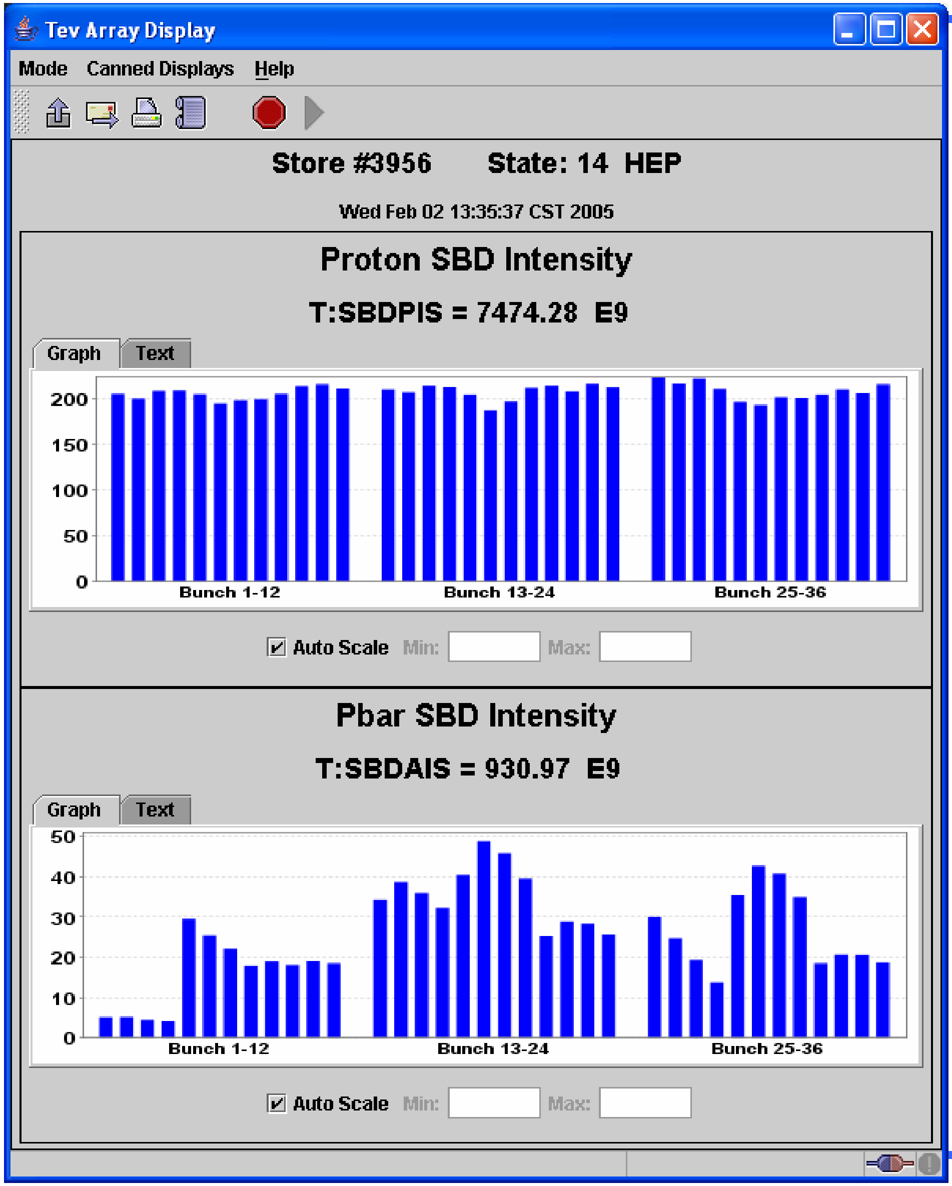
Uncoalesced protons in Tev



Coalesced proton in Tev

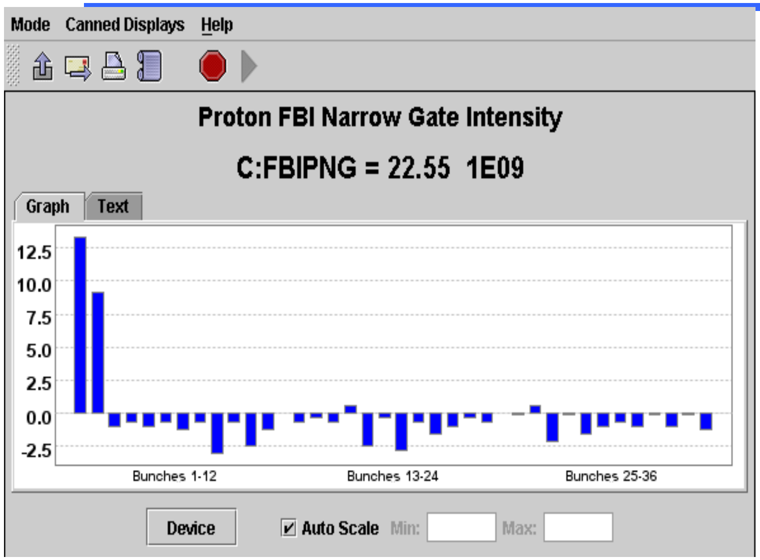


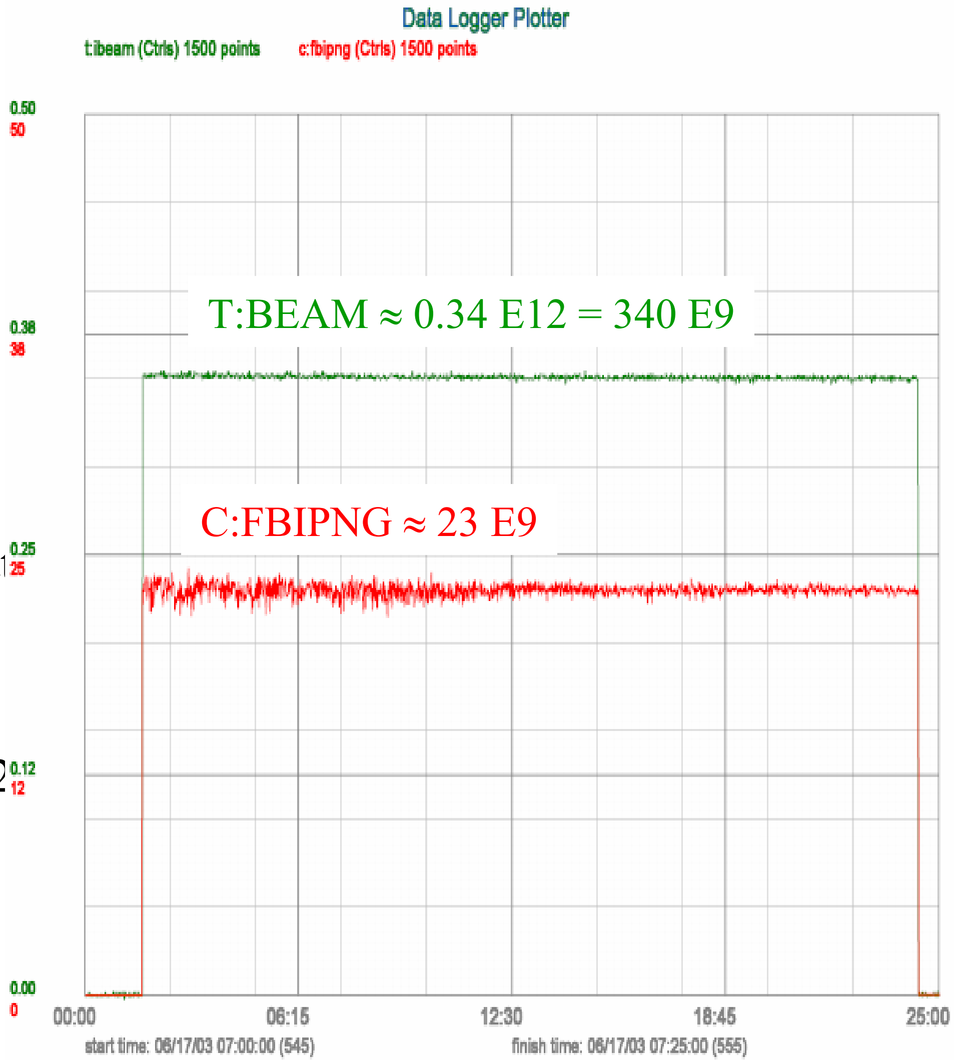
Tev Array Display



- Shows bunch-by-bunch parameters
- Usually running in CDF control room on AD Windows machine
- Useful during injection to see how many COALESCED bunches are in the Tevatron

Two Little Bunches in the Tev?





- No, the FBI devices look only at buckets that should be populated with COALESCED bunches for HEP store
- 2 of the 30 bunches of uncoalesced protons happen to be in the buckets used for P1 & P2
- ***The SBD now distinguishes between uncoalesced and coalesced beam***
  - Will see ~30 bars for uncoalesced protons
- Compare T:BEAM and C:FBIPNG

How can pbar stack be measured in mA?

- The revolution frequency of an 8 GeV particle in the <u>Accumulator</u> (not the Recycler) happens to be ≈1.6 μs
- 1.6 $(10)^{-19}$ Coulomb/pbar / 1.6 $(10)^{-6}$ s = $(10)^{-13}$ Amp/pbar
- $(10)^{10}$ pbars × $(10)^{-13}$ Amp/pbar = 1 mA!
- For pbars in the Accumulator: <u>1 mA = $(10)^{10}$ pbars</u>

Glossary

- **Stack** = antiprotons being stored in the Accumulator
- **Stash** = antiprotons being stored in the Recycler
- **Store** = beam kept circulating continuously in the Tevatron; can be an HEP store (protons and pbars), or proton-only for studies/maintenance
- **Ramp** = accelerating beam from 150 GeV to 980 GeV (in Tev), dipole magnet current increasing to bend beam harder as energy rises
- **Flattop** = Tev ramped to 980 GeV, **before** low β squeeze
- **Squeeze** = Focusing the beams to smaller transverse size at CDF/D0
- **Low Beta** = Tev @ 980 GeV, **after** low β squeeze
- **Initiate Collisions** = turn on electrostatic separators to make beams collide at the centers of CDF and D0
- **Scraping** = Removal of beam "halo" (stuff far away from beam center) by moving stainless steel collimators close to beam; reduces beam losses at CDF/D0; done automatically after collisions begin; takes 12-15 minutes
- **Cogging** = moving the (pbar) beam longitudinally desired location
- **Abort Gaps** = series of empty buckets between bunch trains to allow abort kickers to reach proper voltage to kick beam into dump blocks

Glossary

- **FBI** = Fast Bunch Integrator
  - Provides Tev bunch intensity measurements
- **SBD** = Sampled Bunch Display
  - Gives Tev bunch length and intensity measurements
- **DC Beam** = beam not captured in an RF bucket
  - Can circulate around for minutes before losing energy via synchrotron radiation and striking an aperture (collimator)
- **TEL** = Tevatron Electron Lens
  - Device that shoots a ~few mA electron beam in the Tev beam pipe
  - Used to knock beam out of the abort gaps (reducing CDF backgrounds)
  - Intended to compensate beam-beam tune shift of pbars from protons (not yet)
- **SDA** = Shot Data Acquisition
  - Accelerator data collection/storage for each shot/store; used for offline analysis
- **QPM** = Quench Protection Monitor
- **QBS** = Quench Bypass Switch